REDUNDANT RING STRUCTURES FOR SHIPBOARD DISTRIBUTED COMPUTER SYSTEMS

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THESIS

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SHIPBOARD DISTRIBUTED COMPUTER SYSTEMS

by

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20. Abstract (Cont'd)

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Redundant Ring Structures
for
Shipboard Distributed Computer Systems

by

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ABSTRACT

The potential constraints on a ring structured distributed computing system imposed by the shipboard environment were discussed. The feasibility of increasing distributed ring system availability to meet the requirements were investigated. It was shown that with a multiply linked ring structure, shipboard environmental effects would not severely degrade successful operation of a distributed system. This finding could result in the utilization of distributed ring computing systems with suitably redundant data path schemes as a highly reliable general purpose data processing system on shipboard platforms.

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CRC	Cyclic Redundancy Check
DCS	Distributed Computing System
DRCS	Distributed Ring Computing System
DRCS/TRMP	Distributed Ring Computing System with Triply Redundant Multiple Paths
EOM	Endof Message Token
MIL-Spec	Military Specification
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
SDMS	Shipboard Data Multiplex System
SOM	Start of Message Token
TMR	Triple Modular Redundancy
TRMP	Triply Redundant Multiple Path

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I. INTRODUCTION

The purpose of this thesis was to investigate the feasibility of instituting a high degree of system availability in ring structured distributed computing systems in order to make them compatible with shipboard environments. A significant amount of effort was given to introducing redundant data links and highly redundant ring hardware in achieving this higher state of availability. Prior to the beginning of this study, the distributed ring computing system concepts were studied to ensure that the problems unique to this system study were well understood.

Although the concept of distributing ring computing systems is relatively recent, significant research has been conducted both in the civilian academic environment and at the Naval Postgraduate School. Chapter II examines this background information and gives an overview and functional description of distributed ring system software and hardware concepts.

In the earlier sections of Chapter III, the specific rationale for investigating methods of increased system availability and reliability in a shipboard environment are developed. In the central sections of Chapter III,

specific designs of data path redundancy as possible ways of increasing system availability in distributed ring systems are discussed and resultant system availability calculations are derived. A significant amount of difficulty was encountered in developing the complicated mathematical models for one system design in particular. While several approaches to system availability calculations were attempted, only one proved to produce reasonable results. A detailed discussion of the system calculations developed can be found in the latter sections of Chapter III as well as a discussion of the results of data path redundant designs as they impact on overall system availability improvement.

Chapter IV discusses a potential redundant hardware design of a data ring interface utilizing current microcomputer technology. Finally, Chapter V summarizes the work completed and states the conclusions of this thesis.

II. BACKGROUND

Given the notable advancements in computer system technology, coupled with the decreasing costs of hardware, the concept of establishing Distributed Ring Computing Systems (DRCS) using present micro and mini-computer hardware has become increasingly popular. The main features of this type of system which make it so desirable over other possible system configurations, are the greater flexibility of the system, its reduced costs, and its processor-independent communications protocols.

In view of the above mentioned advantages, applications of the ring structured computing systems to naval shipboard designs appear highly desirable. Historically, the particular information transfer needs of electronic subsystems on shipboard platforms have been met by installing dedicated cabling throughout the hull. With the ring structured communication network, given suitable redundancy in network paths, the situation should never again arise where ship subsystems will be functionally dependent upon a single thin thread of dedicated wiring. The distributed ring computing system with path redundancy will provide multiple, physically separated paths throughout the ship which will

increase information transfer capacity and operational survivability.

Considerable research into configuration and uses of the ring structured distributed computing systems has been conducted by David Farber [Ref. 3] of the University of California at Irvine as well as by students and faculty at the Naval Postgraduate School [Refs. 4, 5, 7, 9, 14]. In reference 11 Professor Farber discusses the increased reliability achieved in a ring structured system by distributing control of the ring among active users with a "Fail Soft" philosophy of control. The concept of "Fail Soft" systems is one where systems exhibit the property of controlled system degradation rather than total failure as a result of component failure. At the Naval Postgraduate School (NPS) a ring data communication system utilizing microprocessor technology has been designed and tested. There is no intention at this time to reiterate the arguments regarding the overall advantages of the ring structured computer systems over other possible configurations. These arguments are more than amply covered in the references. What is intended is to investigate and discuss the system reliability advantages of a suitably redundant version of a ring structured computer information system and to analyze its advantages in higher reliability.

A. BASIC CONCEPTS OF A RING STRUCTURED DISTRIBUTED COMPUTING SYSTEM

A distributed computing system is process oriented. That is, most system services are processes. Within each processor connected to the distributed computing system is a resident software nucleus which provides local resource management and interprocess communication services.

The key element to the distributed computing system is the method of communication between processors. To gain maximum flexibility the system should:

1. Distribute control of the system (no one processor is in control of the system at all times).
2. Execute processes without regard to their physical location.
3. Permit communication between processes without regard for their physical locations.

The first goal is necessary to ensure that catastrophic failure does not occur to the system if one processor or process fails. The second two goals ease the job of dynamic reconfiguration of the system.

In a ring structured system each processor in the network is connected to a unidirectional high speed communication ring by a ring interface (see Figure II-1). Only the processor and associated ring interface in control of the

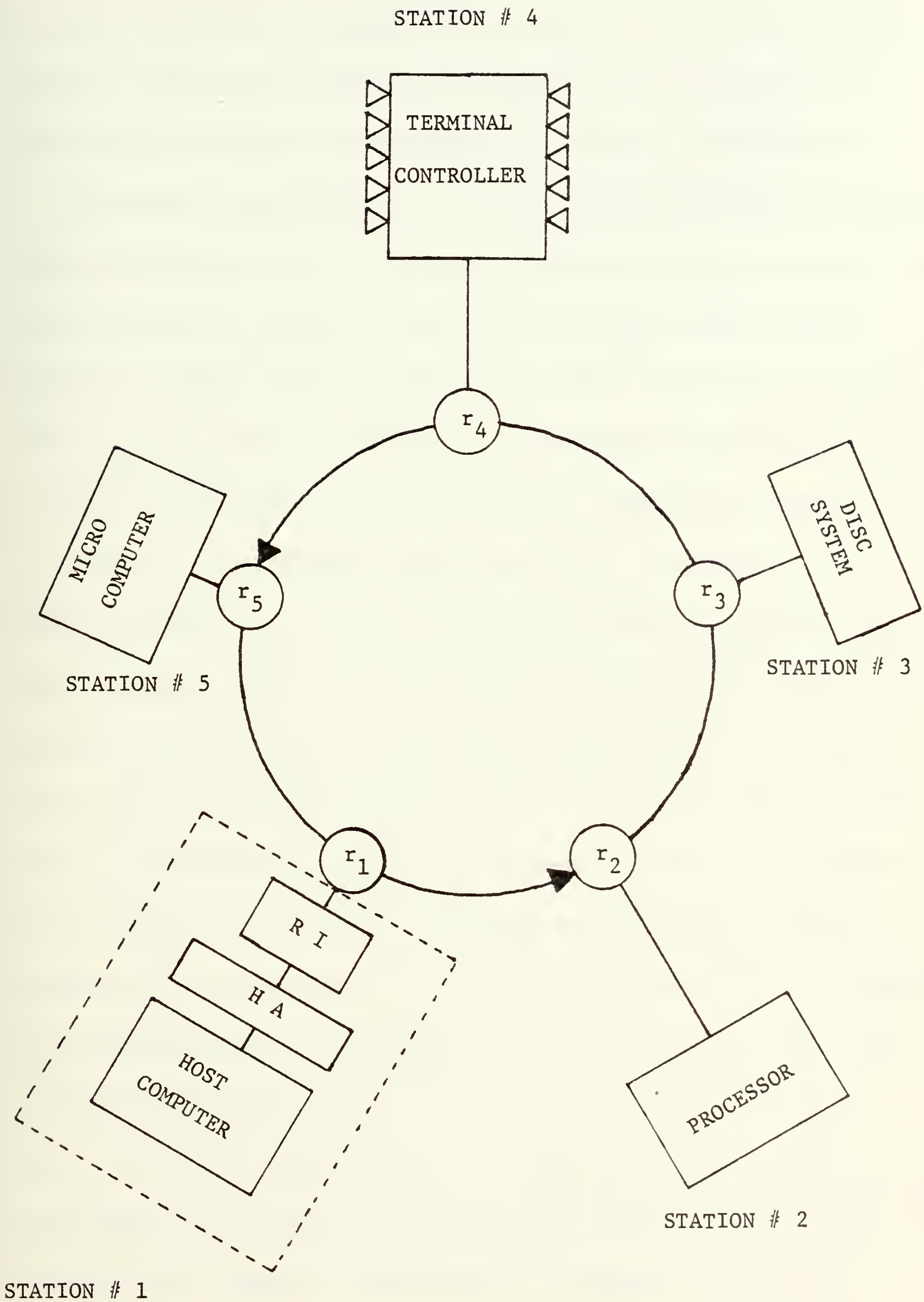

FIGURE II - 1. RING COMMUNICATION NETWORK

system can transmit a message. Messages are directed to a process by name, as opposed to physical location, so that where a particular process resides in the system is not important to the message sender (location independence).

Message transmission is accomplished through a combination of hardware and software. Transmitting a message from one process to another causes the message to be passed around the ring from station to station and to be copied into the processor on which the destination process resides by that processor's ring interface. Each ring interface has a list of the processes resident in its processor. As a message passes by, a ring interface compares the destination process name in the message with the list of process names, copies those messages for which there is a match into the attached processor, and sets status bits at the end of the message indicating whether or not the message was copied, not copied, or copied incorrectly. Notice, however, that while a ring interface is receiving a message from the ring and delivering it to the host, it does not remove the message from the ring. Instead, it merely copies it, one byte at a time. This means that the message continues around the ring and may be sent to more than one process in a single transmission sequence. This accomplishes the second goal, communicating between processes

regardless of their physical location. When the message finally returns to the sending ring interface it is taken from the ring and the status bits are sent to its processor to be checked for successful reception of the message.

Only the ring interface in control of the system can transmit a message. Once the interface in control has completed its message transmission and receipt, control is passed to the next ring interface. In this manner control is distributed among all ring interfaces. The actual control of the ring is passed around by means of a "control token." A ring interface may transmit a single message only when it possesses the control token. This guarantees that only one ring interface has control at one time. Independent timers in the ring interfaces ensure that no one ring interface monopolizes the ring and if control is lost, control will be regained by one of the other ring interfaces. The important thing to consider is that all ring interfaces have the capability to take control of the ring and that only one ring interface will have control at a time under normal operation.

In order to punctuate the continuous flow of data on the ring, two additional control type tokens are defined. The Start of Message (SOM) token is used to tell all receiving ring interfaces that a message is to follow. The

End of Message (EOM) token tells the ring interface two things: First, it tells the ring interface that there is no more information to relay to its host. Secondly, it signals the CRC (error detecting) circuitry to check its remainder for a transmission error. In the basic format of the message sent, the SOM token is followed by the name of the addressee, followed by the message data. At the end of the message is the EOM token which is followed by several bits used to check for proper receipt of the message.

B. HARDWARE COMPONENTS OF A RING STRUCTURED SYSTEM

Each station on the distributed ring structured system is subdivided into functional hardware/firmware components, each having specific responsibilities. Figure II-1 shows a conceivable ring communication configuration where a "station" is defined as a host processor together with its ring interface. In the earlier days of distributed computing systems the ring interface and its associated components were frequently hardwired. Such is the case of the ring interface developed by Farber at the University of California at Irvine [Ref. 3]. At the Naval Postgraduate School, however, a modular approach was taken in designing a cost effective and more flexible ring interface with

emphasis on firmware replacing hardware wherever possible. The following, therefore, is an overview of the functional responsibilities of the key hardware/firmware components of the ring distributed computing system as envisioned at the Naval Postgraduate School [Ref. 4]. Station 1 in Figure II-1 shows the logical subdivision of each station into functional hardware/firmware components.

1. The Repeater

The repeater (r_i in Figure II-1) provides the necessary signal boost to drive messages over long cable lengths. It is designed to be directly connected to the ring, recover the messages, recover clocking information, and pass on cleaned up, reshaped data to the outbound cable. The physical design of the repeater is dependent on several characteristics of the actual system hardware. That is, the cable length between stations, the cable type, the types of receiver/drivers used, and ring speed each in its own way affects repeater design. It should be noted that the NPS hardware/firmware design physically combines the repeater with the ring interface module. In this report most references to the "ring interface" include the characteristics and functions of both of these components.

2. The Ring Interface

In Figure II-1, although different processors are connected to the ring, the functions performed by each ring interface (RI) is to be the same at all stations:

(a) Data and control tokens traveling along the ring are to be received, evaluated and re-transmitted.

(b) Certain checking functions are to be performed and status information is to be sent to the host processor.

(c) Control signals from the host processor must be acknowledged and complied with.

A ring interface incorporates all these functions in the most efficient manner independent of any host processor. Each host processor communicates with its ring interface via a device which adapts the general purpose ring interface to the host computer's specific needs. The module performing this role is the Host Adapter.

3. The Host Adapter

The Host Adapter (HA) in essence acts as an interpreter between the host processor and the ring interface. The host adapter is designed for a particular station and as such is dependent on the host processor being served. In some cases, host processors can be linked directly to

the ring interface with the host adapter functions being accomplished by the host software.

The foregoing has been a general discussion and introduction into the basic hardware/firmware concepts of the ring structured distributed system. For a detailed discussion, reference should be made to Hirt [Ref. 5], Meserve [Ref. 9], and to Harris [Ref. 4].

III. SYSTEM DESIGN

A. FAILURE CONDITIONS IN RING STRUCTURED COMPUTING SYSTEMS

1. The Effects of Battle Damage

One of the more important questions being addressed in this chapter is consideration of system availability for various ring system configurations. Controlled degradation of performance under failure conditions is one of the greatest potential advantages of the ring structured distributed computing system. Almost all previous work with these ring systems has dealt with the single ring system concept which did not have to attempt to survive the most obvious failure modes in a shipboard military environment, that of battle and collision damage and component failure. Since the probability of a shipboard ring being severed by battle damage is very real, it has to be considered seriously. A system failure caused by component malfunction has to be localized and then repaired or bypassed unless there is sufficient redundancy built into the system.

2. System Failure and Maintainability

Aside from the effects of battle damage, the impact of system maintenance on overall system availability must be considered. Given any system where performance requirements

are met, the addition of capability to ensure continuous reliable performance during routine and emergency maintenance situations is essential. This is especially true where system performance criteria require a certain amount of maintenance actions be accomplished. It is desirable to continue system operation even during maintenance actions, when some components will be out of service.

A ring communication system would be particularly affected by the choice of backup capabilities incorporated into the overall system design. For example, consider designing a system where the tradeoffs are increased performance at a cost of more lengthy repair times. If failure is very rare, then repair times are less important. On the other hand, if frequent system repair is anticipated, the excessive repair times with their associated costs and system degradation may far outweigh performance advantages.

Where battle damage, everyday system failures, and maintenance actions occur, it is clear that one possible solution to sustained performance is to include some sort of path (cable) redundancy in the design of the ring to provide alternate message paths when some elements fail. If, as expected, the increase in redundancy will enhance system availability, then the increase in availability

will also directly contribute to the control of degradation of performance under failure or maintenance conditions.

In order to investigate the potential of increased redundancy as a key to enhanced ring system availability, the following sections will describe in detail two alternatives for such availability enhancement using added transmission paths.

B. THE POTENTIAL OF REDUNDANCY FOR IMPROVING SYSTEM AVAILABILITY

1. Protective Redundancy

Redundancy (the availability of more than one means of performing a function when fewer are required) is a principal method of achieving increased reliability. In the two alternative methods to be discussed later in this thesis, active parallel redundancy will be considered to improve system availability.

Where systems are operated together with all operable (unfailed) systems performing the function all the time, a system is said to be active parallel redundant. An aircraft which can still fly when two of its four engines fail is an example of the protection provided by this type redundancy.

2. Application of Path Redundancy to a Distributed Ring Computing System

The potential of damage or disruption to a shipboard ring in a battle environment is very real and critical to a ship's fighting ability. Once a ring system suffers a severed or degraded communication path, link, or repeater, the following conditions must be met to continue operation of the ring:

(a) The condition that the ring has been cut or degraded must be detected.

(b) The disruption in the ring must be located.

(c) The disruption must be repaired or bypassed.

As soon as the ring has been disrupted, the station immediately after the disruption will be aware of the situation. If the ring is without redundancy the system will remain inoperative until the disruption is repaired. It is obvious that some kind of path redundancy must be built into the ring to allow for the localization and/or bypassing of damage to ensure a continuity of operation. The following two system concepts, Triple Modular Redundancy (TMR) and Triply Redundant Multiple Paths (TRMP), provide alternative approaches to the problem of installing path redundancy to the distributed ring system. Both approaches deliver significantly better availability than the single non-redundant ring.

C. SPECIFIC REDUNDANCY SPECIFICATIONS

1. Triple Modular Redundancy (TMR)

The TMR approach for adding redundant paths to the distributed computing ring system described in Chapter II is the most direct and least complex. In the classical "N" modular redundancy approach to the ring system there are some number, N, of complete communication paths between stations on the ring. For the sake of clarity and to reduce complexity of discussion, the Triple Modular Redundant Case (N=3 paths) will be discussed. The concept of three complete paths between stations is analogous to having three complete data rings in the system with the three rings going through each station. Figure III-1 illustrates a TMR configuration for a ring system with five stations.

In TMR, all stations would listen to one of the incoming paths until such time that an error is detected. If an error were detected while a message is being transmitted, the station would wait for a retransmission of the message on the same path. If an error is again detected, the listening station would send on the outbound path detected as providing erroneous data, a high priority message directing each station to switch output path transmissions to a preselected backup path. Once this switching of paths has been accomplished, synchronization procedures must be

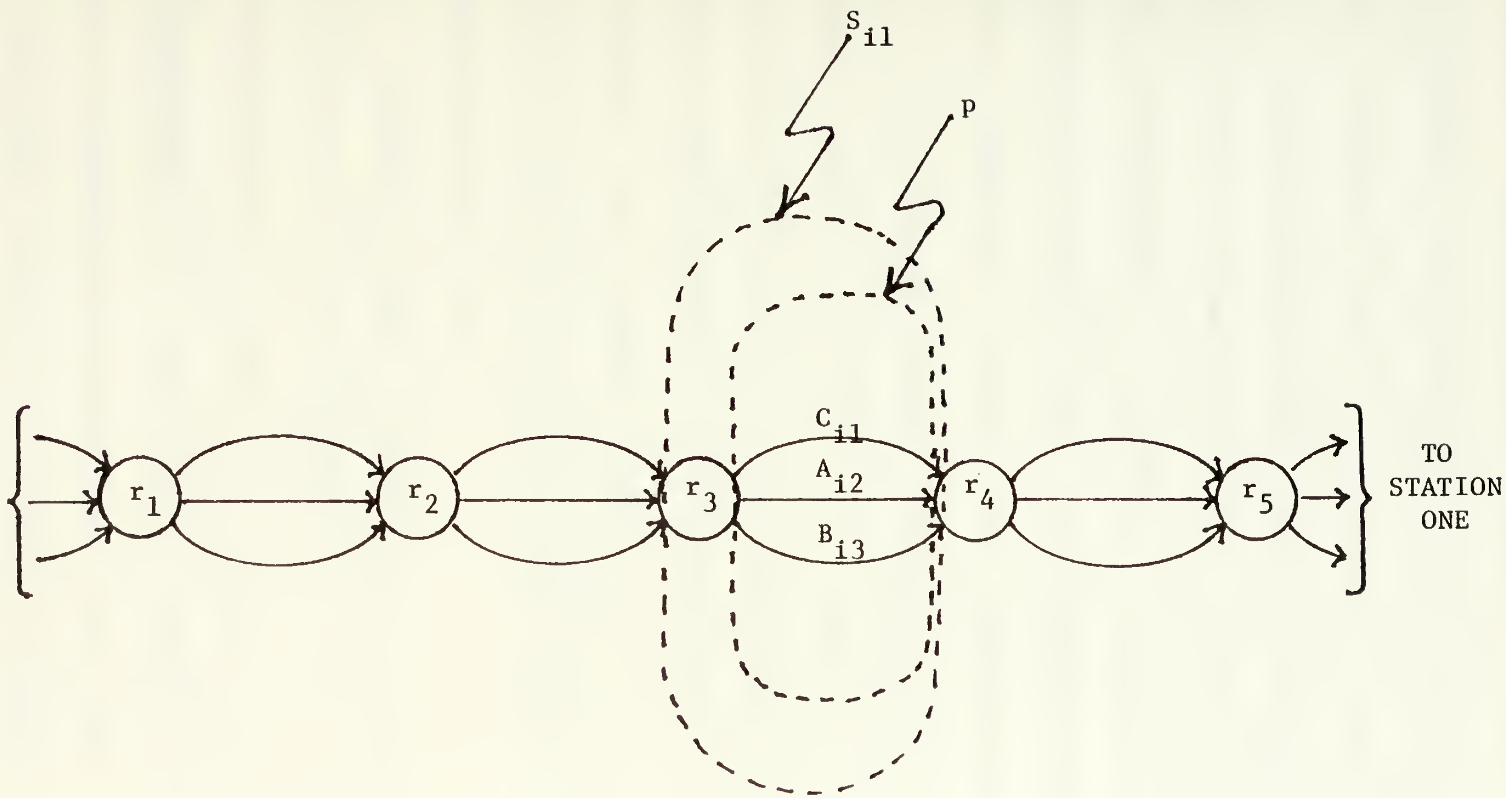

FIGURE III - 1. TMR FOR A FIVE STATION SYSTEM

completed. These specific synchronization procedures which are necessary for initializing the ring are discussed in depth by Harris [Ref. 4], and will not be elaborated here.

Referring to Figure III-1, it can be seen that the five stations are represented in a serial arrangement, each station designated by S_i where i = 1,2,3,4,5. The stations themselves are divided into two separate modules; the repeater module (r) and the data path module (p).

The repeater module consists of the ring interface/ repeater hardware as well as the selector switch circuitry which picks which of the three incoming data paths is to be used as primary path of communication to the host computer. In essence, the repeater module is the cornerstone of each station in TMR since failure of any single repeater module causes a system failure.

Having brought up the topic of system failure, at this time it would be advisable to state specifically, the conditions for an operational system; a system (TMR, TRMP) is <u>operational</u> if: given that a specific station is operating, a transmission path exists such that it is possible for the given station to transmit a message around the ring and back to itself.

It can be seen that both the repeater and data path modules play a key part in system success. The data path

module (p) is composed of the three redundant paths of communication between successive repeater modules (see paths A_i, B_i, C_i in Figure III-1). Each path is the line of communication from the output of one repeater to the input of the following repeater module.

For the purposes of calculating system reliability in TMR, each repeater module (r) and each data path module (p) are assigned a specific availability value. Availability is defined as the ratio of the time that the system is operational to the total amount of time that it is, or may be, needed. The total time is the sum of the usable time and downtime for maintenance/repair as shown in equation 3.1.

$$\text{Availability} = \frac{\text{uptime}}{\text{uptime} + \text{downtime}} \qquad (3.1)$$

Downtime is the result of a number of maintenance/repair actions. The average downtime is sometimes called the mean time to repair (MTTR) and it includes both scheduled and nonscheduled downtimes. Availability can also be expressed as the ratio of the mean time between failures (MTBF) divided by the sum of the MTBF plus the MTTR as shown in equation 3.2.

$$\text{Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \qquad (3.2)$$

The key to the relation between availability and reliability is the MTBF. The greater the reliability, the better the availability, given that MTTR can be held fairly stable.

For the purposes of system availability calculations, all repeaters are assumed identical and their availabilities were taken as equal. Similarly, the availability of all paths are taken as equal where $P(C_i)=P(B_i)=P(A_i)=a_L$. Repeater module availability is labeled a_r with data path availability a_p and station availability a_s. Total system availability for TMR is labeled a_{TMR}.

a. TMR AVAILABILITY CALCULATION

Referring to Figure III-1, it can be seen that TMR System availability is calculated as a function of the repeater module availabilities and the data path module availabilities. Since the data path module itself is triply parallel redundant, the availability of the data path module (a_p) is caluclated as:

$$a_p = 1-(1-a_L)^3 \tag{3.3}$$

The availability of the station (a_s) is the product of the availabilities of the repeater and data path modules:

$$a_s = a_r \cdot a_p \tag{3.4}$$

Having knowledge of the station availability, the overall system availability for TMR (a_{TMR}) can now be ascertained:

$$a_{TMR} = (a_s)^N \tag{3.5}$$

where N = the number of stations on the ring system.

For example, with $a_L = .99$, $a_r = .98$ and N=5,

$$a_{TMR} = \left[a_r(1-(1-a_L)^3)\right]^N = .904$$

To compare the TMR System availability data with a similar system with no redundant characteristics, the following calculations are presented:

$$\text{Given:} \quad a_r = .98,$$
$$a_L = a_p = .99$$
$$N = 5$$

therefore, station availability is:

$$a_s = a_r \cdot a_p = (.98)(.99) = .97$$

Non-redundant system availability is:

$$a_{non\text{-}redundant} = (.9702)^5 = .86$$

Although TMR enhances system availability, a serious potential weakness in TMR is created by the uniqueness of the repeater module (r). From Figure III-1 it can be seen that all triply redundant data path modules (p) must

interface directly with station repeater modules. If one repeater module were disabled, all data paths would be interrupted.

This situation could be alleviated if repeater modules were connected in different sequences. Methods could be devised to utilize selected alternate paths to bypass defective repeater modules without interrupting overall system operations. The Triply Redundant Multiple Path (TRMP) system configuration for distributed rings provides a possible solution to this situation.

2. Triply Redundant Multiple Path (TRMP) System Design

Figure III-2 shows a TRMP system of five stations, having three path redundancy. Only one of the three outgoing data paths from each repeater module links with the immediately succeeding repeater module (see Figure III-2, path C_2, for example). A second outbound path links with the second successive repeater module, skipping past one module (Figure III-2, path B_2). The third outbound path skips the first and second modules/stations and links with the third successive module (Figure III-2, path A_2). Note that each path emanating from every repeater module is labeled A_i or B_i or C_i, where i is the number of repeater.

In future discussion a path C will be said to have a logical "distance" of one, B a distance of two and A a

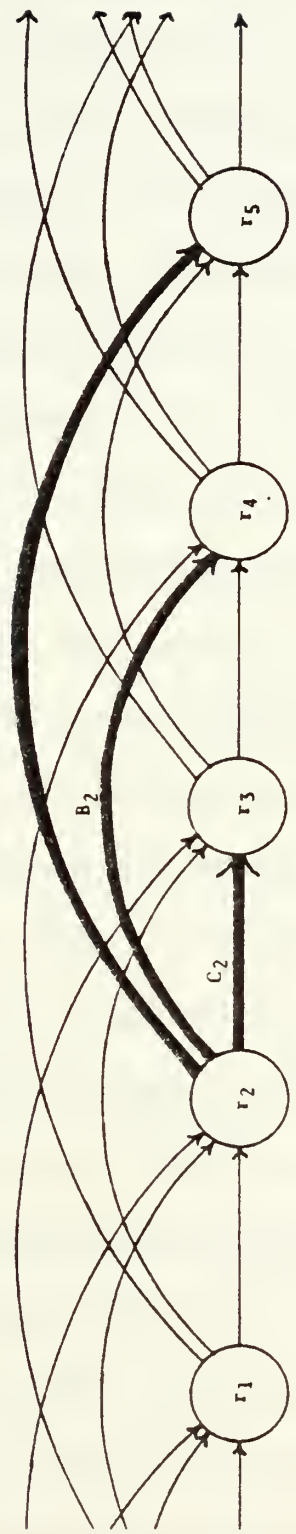

FIGURE III - 2 TRMP SYSTEM, 5 STATION, TRIPLE PATHS

distance of three, referring to the difference between the sequence numbers of the originating and terminating stations. The actual physical lengths of the paths may have any relationship, depending on the placement of stations in the ship.

The arrangement of data paths in relation to station number is the key to TRMP. With TRMP it is possible for two consecutive repeater modules to be inoperative while still having the system working. In addition, it is possible to have combinations of paths and repeaters inoperable while still maintaining an operational system overall.

In a shipboard environment with TRMP distributed ring systems, any ship could sustain damage at many points throughout the ring system with data paths and repeater modules alike being rendered inoperative. It must be pointed out, however, that it could be possible to disrupt all system operation in a battle damage environment through selective disabling of repeater modules and data paths. However, the flexibility of TRMP in coping with potential damage and/or maintenance requirements presents significant advantages over systems with little or no redundancy or even with those having TMR characteristics. This fact will be borne out in later studies of availability calculations.

Because of the unique arrangement of paths in TRMP, only certain numbers of stations may be included in the

overall system (stations in this sense refer only to the ring repeater module connections on the ring). If the number of stations were even, a complete circuit of distance-two links could be formed which locks out half the stations. Similarly, if the number of stations were a multiple of three, a complete circuit of distance-three links could be formed which locks out two thirds of the stations. See Figures III-3 and III-4 for illustration.

The limitation on TRMP then, is that the number of stations on the entire ring system cannot be divisible by two or three. In actual applications, dummy stations could be inserted into the ring to ensure that this limiting condition is met.

a. TRMP OPERATING SEQUENCE

In the TRMP system each station utilizes a switch to select which of the three paths will be monitored for the incoming signal. Outbound data is transmitted on all three outgoing paths. If a station receives degraded or disrupted signals on the path being monitored, it waits until it has timed out or received a second unsuccessful transmission on that path and then switches to an alternate path and repeats the sequence. If all three input paths to a particular station are disrupted, that station receives no further messages and outputs a priority message to the ring

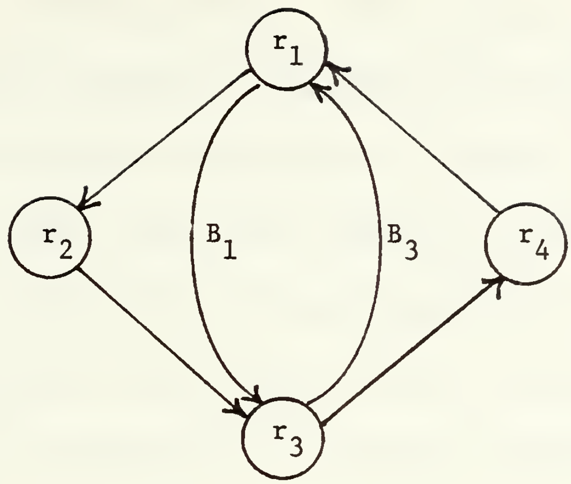

FIGURE III - 3. TRMP WITH A MULTIPLE OF TWO STATIONS

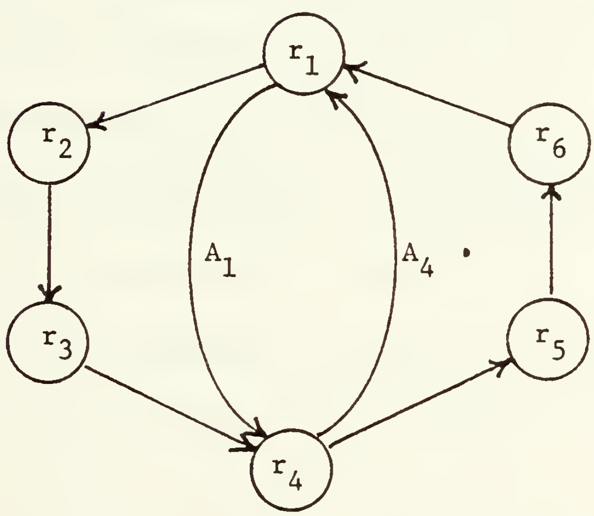

FIGURE III - 4. TRMP WITH A MULTIPLE OF THREE STATIONS

via its three outgoing paths. This message indicates the condition, thus alerting the system users that one particular station is unable to receive or transmit any further messages. In TRMP, while the station in question is cut off from the system, the system continues to function because two alternate paths which bypass the inoperative station allow a continuity of message transmission around the ring.

b. TRMP AVAILABILITY CALCULATION DEVELOPMENT

The calculation of system availability for TRMP is not nearly as straight forward as TMR. From Figure III-2 it will be seen that TRMP is organized with transmission device interfaces/repeaters represented by circles labeled r_i and data paths represented by directed arcs labeled A_i or B_i or C_i. All devices are identical in construction and all data paths are identical as well. A message sequence begins by specifying which of the devices and paths are operational and which are not. Therefore, the first question that must be addressed is, what is the probability that at least one station on the ring is operational (a station in this sense being a combination of host computer and ring repeater). This event will be called S_1 and its probability is found as follows:

The probability that a given station is operational can be expressed as one minus the probability that the station is inoperative.

$$P\left[\begin{array}{c}\text{A}\\ \text{Station}\\ \text{UP}\end{array}\right] = 1-P\left[\begin{array}{c}\text{A}\\ \text{Station}\\ \text{DOWN}\end{array}\right] \tag{3.6}$$

In a distributed ring system where station failures are independent, where individual stations are linked in a serial manner, and where each station in the ring has the same probability of being operational, the probability that every station in the system is not functioning is:

$$P\left[\begin{array}{l}\text{All Stations}\\ \text{in System}\\ \text{Inoperative}\end{array}\right] = P\left[\begin{array}{l}\text{Any}\\ \text{Station}\\ \text{Down}\end{array}\right] \tag{3.7}$$

where N is the total number of stations on the ring.

It follows that the probability of at least one station in the system being operational is one minus the probability of all stations in the system being inoperative.

$$P(S_1)=P\left[\begin{array}{l}\text{At least one}\\ \text{Station}\\ \text{Operational}\end{array}\right] = 1-P\left[\begin{array}{l}\text{All Stations}\\ \text{in System}\\ \text{Inoperative}\end{array}\right] = 1-P\left[\begin{array}{l}\text{Any}\\ \text{Station}\\ \text{Down}\end{array}\right]^N \tag{3.8}$$

In calculating the probability that a given message will successfully transit the ring, some ground rules have to be established. First, each device (ring repeater) functions throughout the message sequence with probability p independent of all other devices. Similarly, each data path functions successfully for a message sequence with individual, independent probability q. Thus, for N devices and associated data paths, a message sequence begins by creation of a message by a functioning device. Each other device may or may not be functioning. The message proceeds by passing over functioning data paths and through functioning repeaters until the message succeeds in again reaching its creating device.

The problem is to determine the probability of a system such that any given message sequence will succeed with specified probabilities in p and q and system size N.

In Figure III-5, which is a linear representation of TRMP, data paths and repeater modules have been labeled to facilitate the calculation of system availability which will follow. To simplify the overall concepts of TRMP, the linear description previously seen is modified in Figure III-5 by adopting directed arcs in lieu of devices.

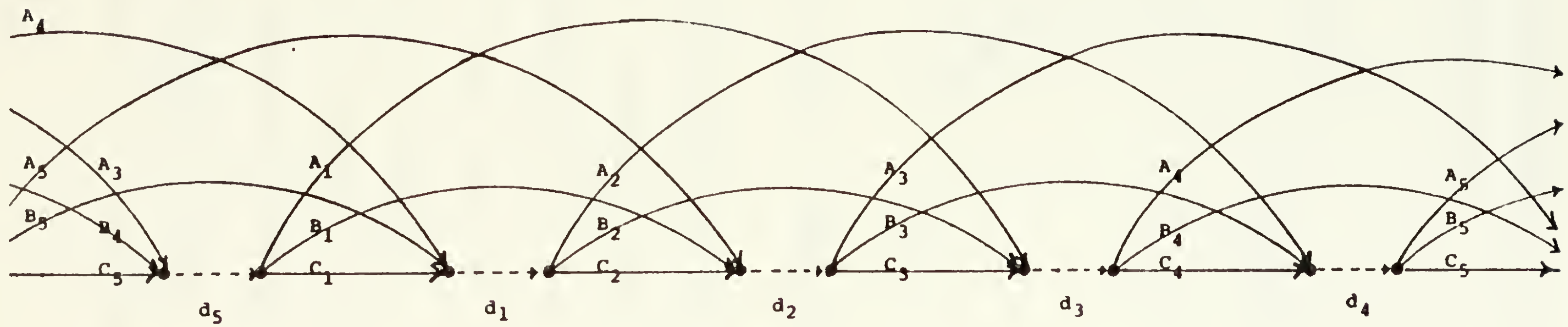

FIGURE III - 5. TRAP WITH DIRECTED ARCS IN LIEU OF DEVICES

As shown in Figure III-6, transmission through the individual station (d_i) is taken as a pair of events, reception (r_i) and transmission (t_i).

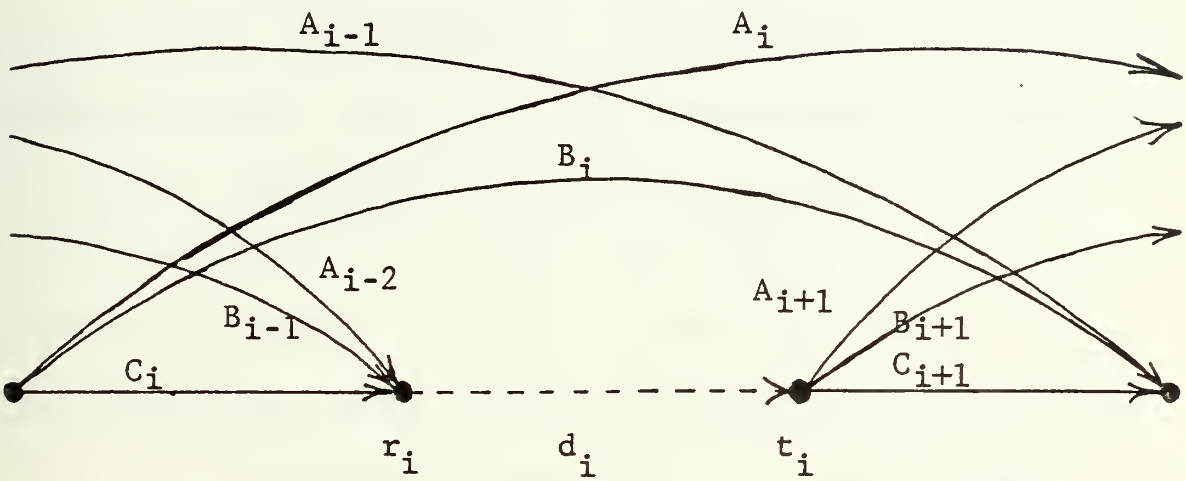

Figure III-6. TRMP Event Structure

The calculation of the probability of system success will use a recursive technique beginning at the origin of the message (at the left in the directed arc diagram, Figure III-5) and proceeding for each event to define the characterization of success. It can be seen that with a triplicated path structure it would be possible for a message to make three complete passes around the ring prior to achieving a successful transit. Therefore a characterization of success will be calculated for three passes of the ring.

In the derivation shown in Table III-1, based on a system depicted in Figures III-5 and III-6, station 5 will initiate the original message.

In Table III-1 each event is doubly subscripted (r_{ij} or t_{ij}). The subscript i represents the specific event number and will vary up to the maximum number of stations on the ring. The subscript j indicates on which of the three passes an event is occurring. For example, r_{31} is the reception at station 3 on pass 1 around the ring and t_{33} is the transmission from station 3 on pass 3 around the ring.

Referring to Table III-1, it can be seen in the originating pass, that successful reception at station 1, (r_{11}), of a message originating at station 5 is defined as the event, link C_1 is up. The message is transmitted from station 1 if it is received (r_{11}) and passes through the repeater (d_i):

$$t_{11} = r_{11} \wedge d_1 \text{ (written } r_{11}d_1\text{)}$$

Correct reception at station 2 can come via the distance-two link from station 5, (B_1), or via the distance-one link through station 1, ($C_2 t_{11}$):

$$r_{21} = a_1 \vee C_2 t_{11}$$

ORIGINATING PASS	SECOND PASS	THIRD PASS
$r_{11}= C_1$	$r_{12}=B_5t_{41} \vee A_4t_{31}$	$r_{13}=A_4t_{32}$
$t_{11}=r_{11}d_1$	$t_{12}=r_{12}d_1$	$t_{13}=r_{13}d_1$
$r_{21}=B_1 \vee C_2t_{11}$	$r_{22}=A_5t_{41} \vee C_2t_{12}$	$r_{23}=A_5t_{42} \vee C_2t_{13}$
$t_{21}=r_{21}d_2$	$t_{22}=r_{22}d_2$	$t_{23}=r_{33}d_2$
$r_{31}=C_3t_{21} \vee B_2t_{11} \vee A_1$	$r_{32}=C_3t_{22} \vee B_2t_{12}$	$r_{33}=C_3t_{23} \vee B_2t_{13}$
$t_{31}=r_{31}d_3$	$t_{32}=r_{32}d_3$	$t_{33}=r_{33}d_3$
$r_{41}=C_4t_{31} \vee B_3t_{21} \vee A_2t_{11}$	$r_{42}=C_4t_{32} \vee B_3t_{22} \vee A_2t_{12}$	$r_{43}=C_4t_{33} \vee B_3t_{23} \vee A_2t_{13}$
$t_{41}=r_{41}d_4$	$t_{42}=r_{42}d_4$	$t_{43}=r_{43}d_4$
$r_{51}=C_5t_{41} \vee B_4t_{31} \vee A_3t_{21}$	$r_{52}=C_5t_{42} \vee B_4t_{32} \vee A_3t_{22}$	$r_{53}=C_5t_{43} \vee B_4t_{33} \vee A_3t_{23}$
$t_{51}=r_{51}d_5$	$t_{52}=r_{52}d_5$	

Table III-1

TRMP Characterization of Success by Event

From the calculations in Table III-1, a generic recurrence in each of the three passes through the system after event r_4 is found to be:

$$r_{ij} = A_{i-2}\ t_{i-3,j} \vee B_{i-j}\ t_{i-2,j} \vee C_i t_{i=1,j}$$

$$t_{i,j} = r_{i,j} \quad d_i \tag{3.9}$$

This recurrence is relatively easy to use for computing system availability by substituting repeater availabilities for d_i and data path availabilities for A_i, B_i, C_i. This process will be discussed more fully later in this section. The main point to remember at this juncture, however, is that if the above concept is applied to a computer program, the values of r_i and t_i are easily stored as linear arrays and the computational effort increases linearly with N.

Combination of the probability of success for each of the three passes will give the probability that a successful message sequence will occur on the originating pass or the second pass or the third pass. This success is expressed as:

$$S_2 = r_{N1} \vee r_{N2} \vee r_{N3}$$

where N = Maximum number of stations in the system.

In terms of probability this same formula is expressed as:

$$P(S_2) = 1-(1-r_{N1})(1-r_{N2})(1-r_{N3}) \tag{3.10}$$

Having previously calculated the probability that at least one station is operational, $P(S_1)$, and the probability of a successful message sequence $P(S_2)$, the overall probability of system success or availability of the TRMP System will be expressed as the product of the two named probabilities, or:

$$a_{TRMP} = P(S_1) \cdot P(S_2) \tag{3.11}$$

c. TRMP EVENT CHARACTERIZATIONS AS PROBABILITY EXPRESSIONS

After development of event characterizations for three system passes, it is necessary to calculate the system probability of success.

The probability of any given successful event from Table III-1 is expressed in terms of the probabilities that certain components are available, and the probabilities of preceeding events. The availabilities of all paths are assumed equal: $P(A_i) = P(B_i) = P(C_i) = a_L$ (for all i). Likewise, the probability that each repeater is functioning is assumed the same for each station: $P(d_i) = a_r$. For example, the event characterization r_{11} is expressed as $r_{11}=C_1$. The

probability of event r_{11} is $P(r_{11})=P(C_1)=a_L$. Likewise the probability of event d_i is $P(d_i)=a_r$.

Paths and repeaters are assumed to fail independently so that,

$$P(t_{11}) = P(d_1 r_{11}) = P(d_1)\cdot P(r_{11}) = a_r a_L$$

The events that "the repeater is operational" and "the path is operational" are not mutually exclusive events however, so the probability of event $r_{21}=A_1 \vee C_2 t_{11}$ is:

$$\begin{aligned} P(r_{21}) = P(A_1 \vee C_2 t_{11}) &= 1-(1-P(A_1))(1-P(C_2 t_{11})) \\ &= 1-(1-a_L)(1-a_L^2\, a_r) \\ &= a_L + a_L^2\, a_r - a_L^3\, a_r \end{aligned}$$

Thus the probabilities of each of the successive event characterizations in Table III-1 can be expressed in terms of a_r and a_L:

$$\begin{aligned} t_{21} = d_2 r_{21} = P(t_{21}) &= P(d_2)\cdot P(r_{21}) \\ &= a_r(a_L + a_L^2\, a_r - a_L^3\, a_r) \\ &= a_r a_L + a_L^2\, a_r^2 - a_L^3\, a_r^2 \end{aligned}$$

Proceeding similarly,

$$r_{41} = C_4 t_{31} \vee B_3 t_{21} \vee A_2 t_{11}$$

so that,

$$P(r_{41}) = 1-(1-P(C_4t_{31}))(1-(1-(1-P(B_3t_{21}))(1-P(A_2t_{11}))))$$

$$= (1-a_L^2a_r-2a_L^3a_r^2+2a_L^4a_r^2-a_L^4a_r^3+3a_L^5a_r^4-2a_L^6a_r^4+a_L^6a_r^5-2a_L^7a_r^5+a_L^8a_r^5) *$$

$$(1-a_L^3a_r^2+a_L^2a_r+a_L^5a_r^3-a_L^6a_r^3)$$

At this point the development of this event characterization was abandoned due to the obvious complexity which had developed and which was increasing with each event.

A simple and straightforward computer program was written to calculate the probabilities of the event characterizations in Table III-1. In each pass, the first few events differ, but most of the calculations are repeated applications of Equation 3.9. The program was written in Fortran IV and used double precision floating point variables. The results of this program are tabulated in the following section in the format of system availability curves illustrating TRMP system availability as a function of system size, repeater availability and data path availability.

3. System Availability Comparisons

The data projected in Figure III-7 illustrates the distinctive advantage that TRMP has over TMR or non-redundant systems. One of the more important aspects that should be noted is that the TRMP configuration can deliver very high

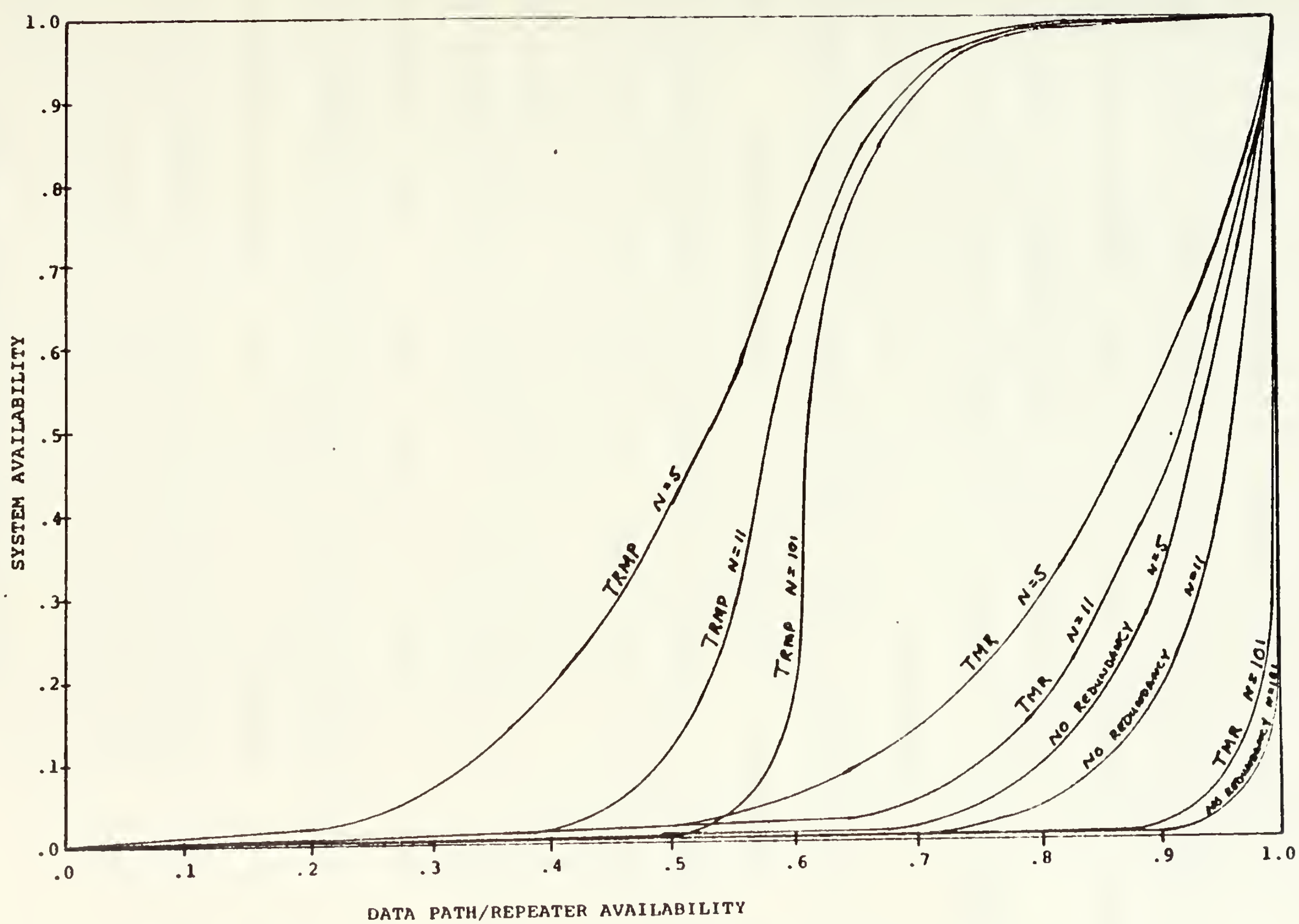

FIGURE III - 7. AVAILABILITIES FOR TRMP, TMR AND NON-REDUNDANT SYSTEM CONFIGURATIONS

availability (approximating .99) even when repeater and data path availability is in the range of 0.8. Additionally, it should be noted that a TRMP configuration of 101 stations is only slightly different from the TRMP system of 11 stations and for this larger number of stations, TRMP availability far exceeds that of TMR or non-redundant systems at all values of repeater/data path availability.

Figure III-8 graphically illustrates the TRMP system probability of failure (1 minus the availability) for systems of varied size and repeater/data path availabilities exceeding 0.9. System probability of failure is graphed instead of system availability because at repeater and data path availabilities exceeding 0.9, the system availability becomes close to 1. Here again the relative closeness of a TRMP system of 101 stations to the system of 11 stations illustrates how a larger number of stations do not significantly affect the high overall system availability for TRMP. It should be noted that TMR and non-redundant configurations were not plotted as their availability curves would appear as nearly vertical lines on the extreme right edge of the figure.

4. <u>Shipboard Data Multiplex System</u>

A system currently under evaluation for the U.S. Naval Sea Systems Command, called Shipboard Data Multiplex

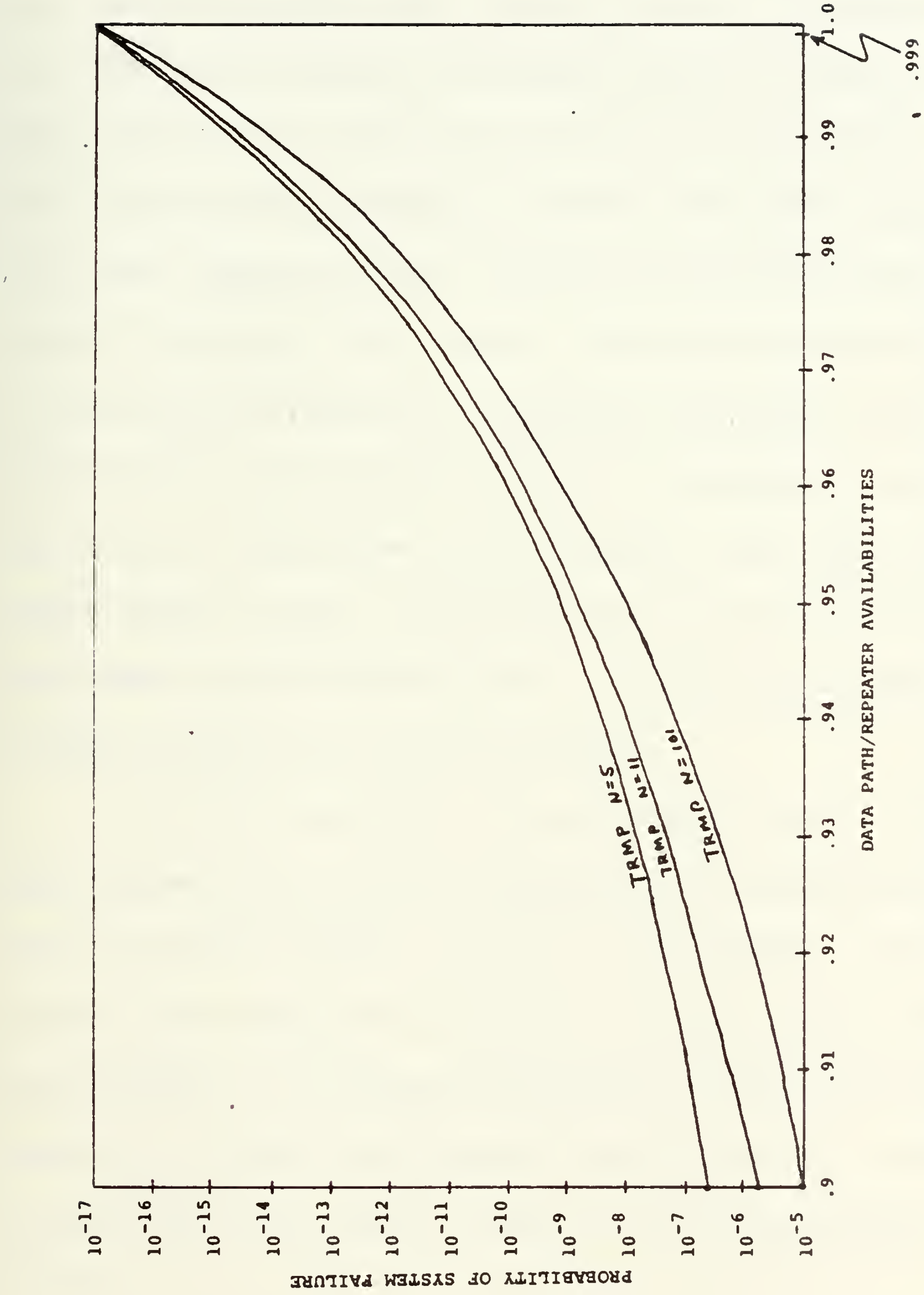

FIGURE III - 8 TRMP SYSTEM AVAILABILITIES WHERE DATA PATH/REPEATER AVAILABILITY > .9

System (SDMS) is similar in many respects to the Distributed Ring Computing System with TRMP (DRCS/TRMP). Intended to be a general purpose data transfer system for shipboard use, SDMS has a modular redundant design. In SDMS there are five separate bus lines (data paths) for a redundant data path transmission capability, whereas DRCS/TRMP utilizes three way redundant paths. While the two approaches are similar in concept they are far different in application. In the SDMS configuration, redundant data paths are both time-division and frequency-division multiplexed whereas distributed ring systems have a single, time shared digital communication stream. Another aspect of path redundancy where SDMS and DRCS/TRMP differ is in the manner and sequence in which stations are interconnected.

One area where the systems differ little is that both systems have totally asynchronous and distributed control of message traffic. Just as in DRCS/TRMP, SDMS has no central processing device which by failing can interrupt data transfer. It has been designed so that failure modes result in a gradual and graceful degradation of system availability rather than a sudden loss of information transfer.

Regardless of their differences, however, each system does provide a higher degree of reliability and

survivability in the information transfer function than do current shipboard systems. In comparing the two systems for overall availability, it is found that both function with very high levels of availability. DRCS/TRMP availability approximates .9999999 when data path and ring repeater availabilities are greater than .95. When repeater availability is increased to .999 the probability of system failure approaches 10^{-17}. Repeater availabilities approximating .999 are reasonable as will be shown in Chapter IV. SDMS, on the other hand, produces an availability in the vicinity of .9999999999. In SDMS, system availability is a measure of the overall system's ability to process 90 per cent of the normal rated traffic demand expected of the system.

For information on the specific system design specifications and operational capabilities of SDMS, the interested reader should consult reference 14.

With a system based on low-risk electronic technology and with many other design principles of DRCS/TRMP, SDMS is worth further investigation as one offshoot of distributed system technology. Its emergence as a viable information transfer system in a shipboard environment indicates that great potential exists for redundant distributed systems.

IV. PROPOSED RING REPEATER DESIGN

A. FUNCTIONAL ANALYSIS OF PROPOSED RING REPEATER DESIGN

The ring repeater discussed throughout this thesis is designed to connect directly to the incoming ring cable, receive the signal, recover clocking information, and pass on reshaped (and possibly retimed) data to the outbound cable. To design the repeater, then, one must know what type of cable is to be used, what transmission distances are required, what type of driver/receivers are to be used and what transmission speeds are used.

A repeater designed to carry out the functions of TRMP was derived mainly from a repeater design discussed by Harris [Ref. 4, p. 80] and is diagrammed in Figure IV-1. Since most developmental work and testing was conducted by Harris no such efforts were conducted during this study. For the purposes of this thesis, the basic design was analyzed from a component availability perspective in an effort to develop the data required for overall system availability.

The function and purposes of the various components of Figure IV-1 are now briefly discussed.

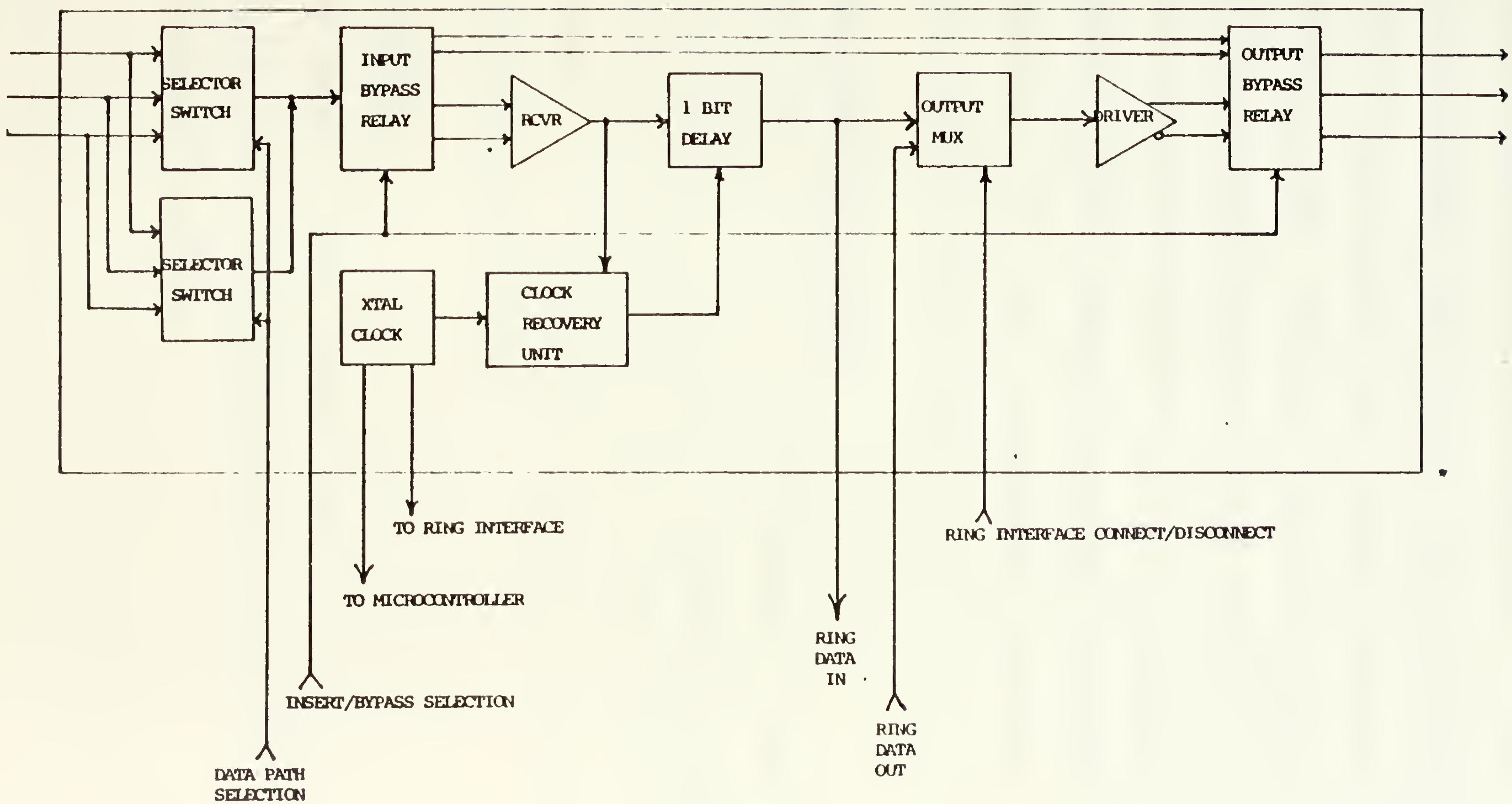

FIGURE IV - 1. REPEATER BLOCK DIAGRAM

Ring Cable

Only a single high speed bitstream is transmitted in this self-clocking ring system. This would suggest the use of single wire, coaxial cable, twisted pair or fiber optic transmission media. Of these four, only the last three are worth considering due to their high immunity to the problems of electromagnetic interference in the shipboard environment. All three of these transmission media are capable of transmitting data at the speed required on board ships and all possess very low failure rates.

Data Path Selection Switch

The purpose of this switch is simply to select the desired data path based on the quality of messages received. It is basically a 3:1 multiplexer which accepts twisted pair inputs and outputs to a bypass relay. Data path selection is determined by the ring interface.

Bypass Relays

The purpose of the bypass relays is to simply switch the repeater out of the ring in case of power failure or for repeater maintenance.

Line Drivers and Receivers

Integrated circuit line drivers and receivers are readily available from many sources. The receiver accepts twisted pair inputs and provides a TTL output to interface with standard logic circuits. The driver accepts a TTL input and transmits to twisted pair cable.

Recent advancements in optoelectronics have produced optically isolated receivers with very high immunity to noise. While earlier models were restricted to lower data rates, recent models now are capable of megabit speeds and are relatively inexpensive. These optically isolated receivers are compatible with many of the differential drivers now on the market. With the increased interest in fiber optic technology this option may prove to be the best way to proceed in future designs.

One Bit Delay

The one bit delay is a single flip flop driver at the recovered clock rate and serves to retrieve the received signal before retransmission.

Clock Recovery Unit

The recovery unit recovers clocking information from the incoming data stream. The bitstream in the ring is self-clocking in that frequent one-zero (and zero-one)

signals are guaranteed during incoming messages. Clock pulses can be regenerated at these transitions. Data bits on the ring are sent in 2 bit periods as shown:

"one" bit : 1 0

"zero" bit : 0 1

During receipt of the tokens (CTL, SOM, EOM) up to three bit periods may pass with no transitions. The clock recovery circuitry provides the sufficient "inertia" to continue with minimal frequency drift during these periods.

Crystal Clock

The 3.58 MHZ "TV" Crystal, crystal clock mechanism used in this repeater design is very stable and rather inexpensive. With proper division it would be used to provide a reference for the digital phase-locking in the clock recovery unit.

Output Multiplexer

A two-to-one multiplexer is used to route ring data from the delay flip-flop to the ring or from the ring interface to the ring. The multiplexed path is controlled by the connect/disconnect line from the ring interface. Note that the ring interface in Figure IV-1 "listens" to the passing data, watching for a CTL token, before entering the ring

(switching the multiplexer to "connect mode"). In this manner the ring data in line is always valid (when the repeater is not bypassed) and is derived from the output of the delay flip-flop.

1. Availability Analysis of Proposed Ring Repeater Components

Throughout earlier system availability discussions in this thesis, the availability of the ring repeater has always been a central or key element to all calculations. Whether TMR or TRMP, the degree of availability of the ring repeater had significant impact on the overall system availability. Realizing the importance of the repeater in availability calculations, it is vital, when designing a repeater configuration, to design a unit that would provide the desired service and also provide that service as much of the time as possible.

As can be gathered from previous discussions on the subject, reliability is the problem at all levels of electronics, from materials to operating systems. Reliability of materials is an "involved" topic which will not be discussed here but it is sufficient to say that in reliability of operating systems, it is often found that system reliabilities have to be known prior to system use. For example, it can be seen that the reliability of an electronic component

is known with certainty after it has been used in the field until it is worn out and its failure history has been recorded. But this approach has not proven very reasonable in situations where the demands of technology required immediate use of electronic components. There was not time to run life cycle evaluation on the component to judge its reliability.

There is then a need to be able to predict the reliability of a component to a very accurate degree. A fundamental limitation on this prediction process is the ability to accumulate data of known validity. Another limitation is exerted by the type of prediction technique used. Very simple techniques omit a great deal of detail and the prediction suffers inaccuracies. More detailed techniques can become so bogged down in detail that the prediction effort becomes too costly or worse, causes delay in actual hardware development.

For the military application there is a set of definitive guidelines to reliability prediction for electronic components. These guidelines, found in reference 13, take into account the specific types of electronic components used throughout the military and utilize the most acceptable prediction techniques available.

The reliability prediction formula used in the following pages comes from reference 13 and reflects the overall device (component) failure rate for MOS Digital SSI/MSI devices. From component failure rates, it will be possible through standard availability calculation methods to eventually ascertain whether the design will meet requirements for reliable performance in the TRMP system. A failure rate will be calculated for each component in the proposed ring repeater design. These failure rates will then be transformed into component availabilities. With these individual availabilities, the overall ring repeater availability will be calculated.

a. REPEATER COMPONENT FAILURE RATE AND AVAILABILITY CALCULATIONS

For MOS Digital SSI/MSI devices the individual device failure rate (λ_p) is specified by:

$$\lambda_p = \pi_L \, \pi_Q \left(C_1 \pi_T + C_2 \pi_E \right) \tag{4.1}$$

where:

λ_p - is the device failure rate in failures per 10^6 hours,

π_L - is the device learning factor. It applies values based on whether device technology is new or time tested (new is usually considered to be less than 6 months old).

π_Q - is the device quality factor. Depending on which MIL-SPEC standard, if any, is applied to the device it assigns an appropriate value.

π_T - is the temperature acceleration factor. Its value depends on device technology as well as the expected temperature range in the environment in which the device will be located.

π_E - is the application environment multiplier. Its values are determined by the application environment in which the device will operate.

C_1, C_2 - are the circuit complexity factors. Values are assigned based on the number of gates within the device.

In using the formula for λ_p , the individual parameter values are determined from appropriate tables found in reference 13.

In Table IV-1 the failure rate and availability for each individual component is calculated.

For all calculations in this table, π_Q (device quality) was set at a value of 150 (commercial or non-MIL-SPEC parts) with no screening beyond the manufacturers regular quality assurance. π_L (learning factor) was set at 1 since any device in production for more than six months

COMPONENT	DEVICE NR	NR OF GATES	Q	L	E	T	CIRCUIT COMPLEXITY C_1	C_2	P	DEVICE AVAILABILITY
4 Bit Binary Counter *	74193	20	150	1	5.0	.25	.0098	.011	8.6175	.99991
1-shot Multivibrator*	74122	2	150	1	5.0	.25	.0021	.005	3.82875	.99996
Positive OR Gate *	7432	4	150	1	5.0	.25	.0033	.0064	4.92375	.99995
HEX Inverter *	7404	0	150	1	5.0	.25	.0013	.0039	2.97375	.99997
Output Multiplexor	74157	14	150	1	5.0	.25	.0077	.010	7.78875	.99992
Line Receiver	DM 8820	2	150	1	5.0	.25	.0021	.0050	3.82875	.99996
Line Driver	DM 8830	2	150	1	5.0	.25	.0021	.0050	3.82875	.99996
Flip Flop	7474	6	150	1	5.0	.25	.0043	.0074	5.71125	.99994
4-1 Multiplexor (Switch)	10174	12	150	1	5.0	.25	.0069	.0095	7.38375	.99992
2-1 Data Selector	74258	12	150	1	5.0	.25	.0069	.0095	7.3875	.99992
1 of 4 Demultiplexor	10173	13	150	1	5.0	.25	.0077	.010	7.78875	.99992
Crystal Clock *		0	150	1	5.0	.25	.0013	.0039	2.97375	.99997

*Make up clock recovery unit

Q = 150: Specifies commercial (or NON MIL SPEC) parts with no screening beyond the manufacturer's regular quality assurance.

L = 1: Specifies a device in production > 6 months.

E = 5.0: Specifies Naval unsheltered environment.

T = .25 : Specifies an ambient temperature of 85° F.

Table IV-1. Repeater Component Calculation Parameters and Availability

received this rating. π_E (environment factor) was set at 5.0 to conform with a Naval unsheltered environment which would be the worst case encountered on a shipboard platform. π_T (temperature acceleration factor) was set at .25 to conform with an expected ambient temperature of 90°F, again a worst case situation. Circuit complexity factors (C_1 and C_2) were a function of the individual number of gates per device and as such varied from device to device.

To illustrate the calculation process, take for example the line receiver. Signetics Corporation device DM 8820 was chosen as a representative component for this calculation. Device DM 8820 has 2 gates which equates to complexity factors of $C_1 = .0021$ and $C_2 = .0050$. All other variables being as stated previously, equation 4.1 results in $\lambda_p = 3.82875$ failures/10^6 hours. To find the number of failures per hours (λ), λ_p is multiplied by 10^{-6}. MTBF is then found by taking the inverse of λ . Having calculated component MTBF it is essential to translate this information into an availability value. The equation originally considered in determining component availability was of the form:

$$\text{Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \qquad (4.2)$$

Direct calculation of the form $A = \frac{MTBF}{MTBF + MTTR}$ is quite simple. When MTTR $\ll$ MTBF, an approximation is more practical:

$$\frac{MTBF}{MTBF + MTTR} \approx 1 - \frac{MTTR}{MTBF} \qquad (4.3)$$

In the case of the proposed ring interface design, the MTTR is expected to approximate one hour. This means, of course, that MTTR is significantly less than MTBF, so the approximation form is used in all calculations for component availability.

To continue with the actual calculations of component availability, equation 4.3 is applied with MTTR = 1 hour. Device availability then, is found to be .99996. What remains is to calculate the overall availability of the ring repeater using all the individual component availabilities generated in Table IV-1.

b. CALCULATION OF THE PROPOSED RING REPEATER AVAILABILITY

From Figure IV-1 it can be seen that repeater availability is, in fact, a serial calculation. Having calculated individual component availabilities it is necessary to first calculate the clock recovery unit availability from its components and then calculate the parallel availability of the two data path selector devices.

The clock recovery unit availability is a serial calculation which results in a unit availability of .99979. The data path selector device has an individual availability of .99992. The availability of the parallel combination of those devices is .999999993. Applying these two availability values as well as the remaining component availability values in Table III-1 to Figure IV-1, the repeater availability is .99933.

2. Increasing Repeater Availability

While the calculated availability for the proposed ring repeater is .99933, this value in practice is not as high as would be desired. There are of course, several alternative approaches which can be used to bolster repeater availability. First would be to consider components of high reliability as reflected in higher levels of the Military Specification (MIL-SPEC) program. It should be noted that components utilized in calculation of the proposed repeater availability were of commercial, non-MIL-SPEC quality. To illustrate, consider the line receiver device (DM 8820) used in the proposed repeater design. Using a commercial configuration, it can be seen from Table III-1 that device availability is .99996. Now, utilizing an otherwise similar device satisfying the most

rigid MIL-SPEC standards, formula 4.1 yields an availability of .9999997.

A second way to increase repeater availability would be to make the entire design more redundant. That is, instead of single devices (as presently proposed), install all devices in parallel. Again to illustrate the effects, the existing proposed design with only the selector device in a redundant configuration, has a unit availability of .99933. By installing every device in parallel using the same commercial quality devices, the resultant repeater availability would be .9999948.

Further calculations are not necessary to conclude that even higher availabilities could be achieved through combination of more rigid MIL-SPEC criteria and more redundant configurations.

One last option for enhancement of repeater availability would be the development of a single integrated circuit device which would accomplish the functions of the repeater. This approach would significantly reduce the number of gates as well as the complexity factors and as a result would increase repeater availability. Any attempt to predict an availability for such a device would be preliminary as the final number of gates (complexity) would be subject to final design specifications of the manufacturer.

In summary, while the availability for the proposed repeater design is well within limits to ensure high overall TRMP System availability, there exist several avenues for enhancement of present or anticipated repeater designs.

V. SUMMARY AND CONCLUSIONS

The main purpose of this thesis was to study the feasibility of enhancing ring structured distributed computing systems by initiating a high degree of redundancy in order to provide high availability necessary for insuring compatibility with shipboard environments. A background study, overview and functional description of distributed ring software and hardware were presented in Chapter II. The major system constraints and environmental problems likely to be encountered in a shipboard environment were described, together with potential approaches for solving these difficulties, in the earlier sections of Chapter III. Specific designs utilizing data path redundancy for increased system availability were discussed and calculations for each design were explained in the later sections of Chapter III.

One such data path design, Triply Redundant Multiple Path (TRMP), provided significantly improved system availability even when individual components of the system were exhibiting unrealistically low availabilities. The TRMP configuration, when coupled with the distributed, asynchronous control philosophy of the distributed ring computing system, would provide a highly reliable approach to network

architecture in shipboard platforms while providing the full benefits of graceful degradation associated with the distributed control concept.

While TRMP appears feasible, there are still many aspects of this design that require further study. It is recommended that further investigation be conducted in the areas of system software and communication protocols for a TRMP type system. In addition, the development of software diagnostics to aid in fault isolation is a key feature to the continued development of this concept. Practical implementations of distributed ring computing systems can be expanded to include TRMP data path configurations so that actual system availability data based on real time application will be available.

In conclusion, it is felt that TRMP provides the degree of redundancy in ring structured systems to ensure high availability in shipboard environments. Even at system repeater and data path availabilities approximating .8, TRMP delivers significantly higher availabilities than other configurations considered. With repeater architecture as simple in design as it is, a repeater availability at or exceeding .999 is attainable. Given this level of component availability, TRMP meets even the highest standards for overall data communication system availability.

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